Using Dynamic Capability Evaluation to Organize a Team of Cooperative, Autonomous Robots

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Abstract

In our research, we have developed an architecture and computational structure that allows for a generic team of robots to dynamically discern what their capabilities are and then apply those to evaluate if the team can achieve an externally mandated set of goals. We define the process of *dynamic capability evaluation* to determine if a team of robots can build a cooperative organization with the necessary capabilities to satisfy a set of stated organizational goals. Based on this evaluation, the organization will decide whether to organize and proceed, relax some goals, or abandon the process of organization.

***Index terms*—Dynamic capability evaluation, Cooperative Robotics, Organization**

1. Introduction

There are numerous examples of teamwork and cooperation in everyday life. Large organizations, such as universities, government agencies, and corporations experience constant inflow and outflow of employees, with each change altering the global capability structure. The continuous change of people and goals that occur dictate a nature of organizations where capabilities must continuously be evaluated to allow operation at the highest level possible. While dynamically evaluating capabilities seems a task with minimal assumed complexity, in a human framework, from a formal computational, process and implementation perspective, it is very difficult and complex.

There has been a great deal of investigation conducted in the area of teamwork, often from an agent perspective [1, 2]. A fundamental necessity of effective teamwork is deciding what available robot or agent plays what role. The ability for an organization to assign roles dynamically has been explored and documented [3]. We will descend further into the organizational process to examine the evaluation of capabilities and how capabilities are the base of the decision making framework, within the process of organization [4].

The evaluation of who plays what role is decided over a set of constraints. Some of the notable constraints are:

- Who is available to be included in the organization?
- What capabilities are required of a role?
- What capabilities does each available agent possess?
- What limitations to play a role exist? (If two available agents can play the same role but only one can play another required role, organization is by the least capable agent, as they may not be capable of doing anything else.)

Cooperative robotic teams can solve problems requiring many critical and non-critical goals to be accomplished. For the teams to be effective, roles must be satisfied by employing robots with the appropriate capabilities to complete the goals required by the role they are assigned. The determination of the effectiveness of a robot playing a role, is based on how well its set of intrinsic capabilities match the requirements of the available role. As a group self-organizes, it must fill each required role with an agent, possessing the appropriate capabilities, to execute the operations required of the role. This self organization must meet the global goals of the organization [5].

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE **2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**
4. TITLE AND SUBTITLE **Using Dynamic Capability Evaluation to Organize a Team of Cooperative, Autonomous Robots**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Kansas State University,Department of Computing and Information Sciences,234 Nichols Hall,Manhattan,KS,66506**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT **see report**		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

The objective of this research is to define a computational structure that formalizes a dynamic link, mapping a set of goal requirements, through an organization of robots, to determine if the robots possess the set of hardware and computational capabilities, to satisfy the pre-determined set of goals. The dynamic derivation of the capabilities of an organization will allow an organization to determine if it possesses the necessary capabilities to accomplish a set of goals before completing the organization process and beginning action to accomplish the goals. This is a complementary technique parallel to network evaluation of teams [6].

The paper will detail the cooperation and organization aspects in section 2. In section 3, the notion of capability taxonomy is described. Section 4 discusses how dynamic evaluation works and how it is applied to a cooperative robotic team. Sections 5 and 6 discuss the architecture and implementation, respectively. Section 7 shows the results and section 8 proposes future research directions we will explore.

2. Cooperation and Organization

We define a cooperative robotic organization as a group of robots acting in specific roles to accomplish a set of discrete goals. The team operates together looking at the needs of the whole and the global team goals as the overriding priority. To create a cooperative team, a template or structure must exist in which to model the team. We have developed an organizational model that meets the requirements of self-organizing, cooperative teams. The organization model [7], as shown in figure 1, describes the relationships between all of the static organization model elements. In particular, we will focus on the Goal, Role, Agent and Capability elements of the model as they are the keys to dynamic capability evaluation. There must also exist a transition function allowing transition from one organization instance to another to support the process of reorganization.

The main elements of the organization model we utilize in this research, are goals, roles, agents and capabilities, so further definitions are provided.

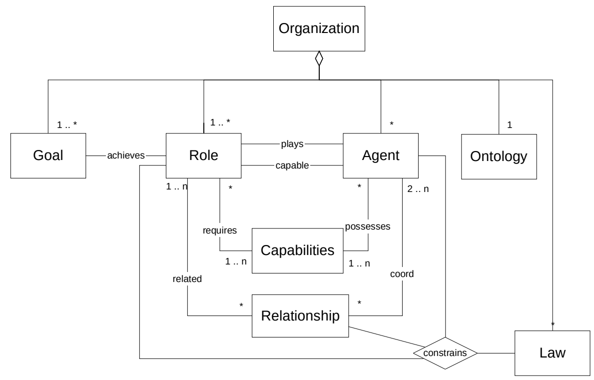

Figure 1: Static Organization Model

Goal: Abstract entities that often must be decomposed to have deliverable outputs and used to identify the critical aspects of system requirements.

Role: Describes an entity that performs some function within the system, analogous to roles played by actors in a play or by members of a typical company structure.

Agent: Equivalent to autonomous robots in this instance. Agents coordinate through the organization via conversations and act proactively and cooperatively to accomplish global and individual goals.

Capability: Robots are defined by the physical and computational capabilities they possess. The robot's capabilities define the roles they can play in meeting a team goal. For robots, there are two levels of capabilities: computational and physical. The computational capabilities are defined by the level of intelligence built into the robot. The physical capabilities are defined by the range of sensors and effectors included as part of the robot's design.

2.1 Organization Process

The organization process takes as input a collection of goals, roles and agents and uses laws, constraints, ontologies, relationships and capabilities to assemble a discrete organization. The process will go through a series of steps to complete the organizational process. The high-level description of that process is as follows:

1. Define the goal(s) of the proposed organization
2. Decompose the overall goal into a goal structure
3. Develop a set of roles to accomplish the tasks
4. Define what robots are available to participate
5. Assess the individual robot capabilities
6. Assign roles to agents by capabilities

At this point, the new team is ready to initiate action to satisfy the organization goals. This is also the point to evaluate if the collective team capability fits all goal requirements. There are three possible outcomes from this evaluation:

- *Goal Satisfaction*: All critical and non-critical goals can be met by resources within the organization
- *Goal Relaxation*: All critical requirements can be met but some non-critical goals cannot be met
- *Goal Abandonment*: At least 1 critical goal cannot be met

3. Capability Taxonomy

Capabilities must be structured in order to be evaluated. To build this structure or taxonomy, we developed a classification scheme that descends from a capability abstract type to a specific capability based on some computational or physical function. In our model, there is a standard structure that can be applied to numerous robotic instances although we have limited it for simplicity and clarity. Most levels of the taxonomy are independent of the robotic instance, by design. The capabilities of many robot models and instances were cataloged and the capabilities were then organized to extract capability patterns, similar to a data mining exercise, to develop a generic taxonomy model. The highest levels of the taxonomy are abstract whereas the lowest level is robot dependent.

To be clear, we will not dynamically create the capability taxonomy itself. The taxonomy will be used as a knowledge representation structure which can be used to interpret the individual capabilities of an agent or robot.

The Nomadic Technologies Nomad Scout robot, used for this example, is pictured in Figure 2. It was chosen for its simple design and small set of sensors and effectors. The model shown in Figure 3 captures the capability taxonomy model of the Nomad Scout robot. At the most abstract level, the Nomad Scout possesses capabilities. The next level of decomposition has sensors and effectors. These elements will be evident in most agent and robotic instances. The next level contains tactile and non-tactile sensor types and motivational and manipulation effectors. Our Nomad Scout has two non-tactile sensors, sonar and infrared,

Figure 2: Nomad Scout Robot

and one tactile sensor, a bump ring. The Scout has one motivation effector, the ability to roll and one manipulation effector, the ability to push.

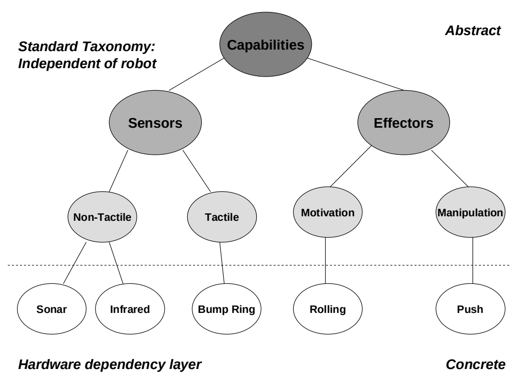

Figure 3: Nomad Capability Taxonomy Model

4. Dynamic Capability Evaluation

The idea of dynamic capability evaluation is to determine, *a priori*, the ability of a group of robotic instances to form an organization and complete the set of required organization's goals. To carry out the evaluation, a query will be executed for each robot instance to evaluate the individual capabilities. These will be matched against the overall requirements of the organization. The process is described by Figure 4. In this case, there is a simple search and rescue effort that requires a role of rescuer. The capability requirements of the rescuer role are:

- *Sonar* for locating the position of the victim
- *Active* grasp to retrieve the victim
- *Roll* to move to the victim and return

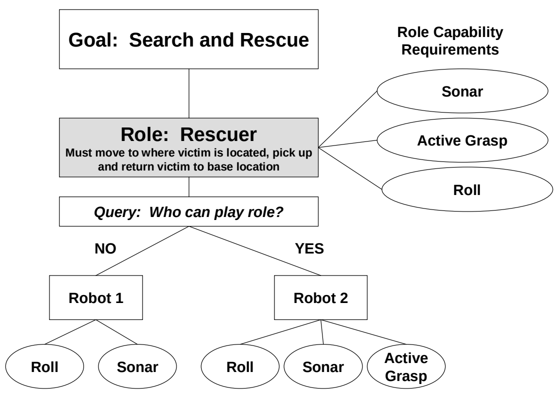

Figure 4: Dynamic Capability Evaluation

Upon understanding the capability requirements of the rescuer role, the organization can then query each available robotic instance to determine if there is any robot to play the role. In the example, Robot 1 has the capabilities of rolling and sonar. Upon comparing the requirements, this robot does not possess the capability of active grasping, so it cannot accept the role of rescuer. Robot 2 has all required capabilities to play the rescuer role so it is accepted as the rescuer.

5. Architecture

The main goal is to design and build an abstraction architecture to provide access to the set of all robotic capabilities, possessed by the organization, regardless of the physical configuration. The abstraction architecture must provide equal access to the capabilities of all involved robotic instances, for determination of the individual and global capabilities.

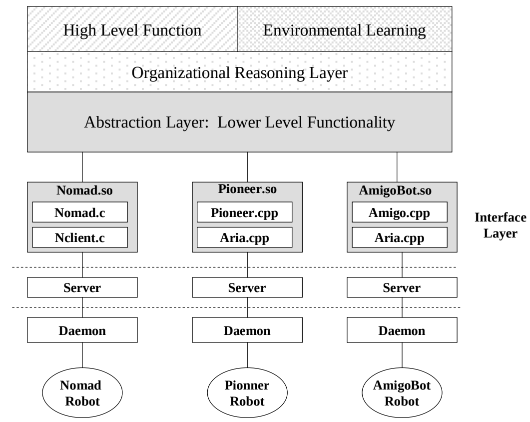

Figure 5: Abstraction Architecture

The initial architecture, shown in Figure 5, is used as one of the software tools to implement this research. The software platform was developed for a prior project and was used as a baseline for this project [8]. Each robotic instance will have a unique interface layer that will connect to the physical robot. The *Interface Layers* communicate with the *Abstraction Layer*. The *Abstraction Layer* is a software interface that allows the *Organization Reasoning Layer* to be indifferent over what robots are assigned to play specific roles. The *Abstraction Layer* is the key enabling technology for the organization to allow dynamic capability evaluation. The *Organizational Reasoning Layer* makes requests for capabilities and robots to fulfill roles by being instantiated as a specific agent, based upon its intrinsic capabilities.

6. Implementation

The implementation of this research was performed first in a Java simulation environment and then in a physical environment. The simulation environment was used to determine if the organizational model elements were field ready and would be robust enough to support an organization of robotic agents. The application of the minimal organizational model was then applied to a team of robots to fully test the developed dynamic capability evaluation techniques.

The implementation considered organizations composed of the Nomad Scout robot combined with ActivMedia Amigobot and Pioneer 2 robots, pictured in Figure 6. These robots were chosen because they represent instances sharing a similar set of base capabilities. Each robot also has at least one unique capability the others do not possess. To describe the differences, the capability taxonomies for the Amigobot and the Pioneer 2 robots are shown in Figure 7 and Figure 8, respectively.

Figure 6: Amigobot and Pioneer 2 robots

The result of each test is whether the execution ends in the correct outcome, where the available outcomes are *goal satisfaction*, *goal relaxation* or *goal abandonment*. Each test uses a randomly generated set of goal requirements that pull from a discrete list. Each test will use a random number of actual capabilities that the available set of robots must possess. If the evaluation is successful in determining that all capability requirements have been met, permission to continue with the organization process beyond the evaluation of capabilities is granted. For this research, we will not proceed beyond the decision point of the capability evaluation.

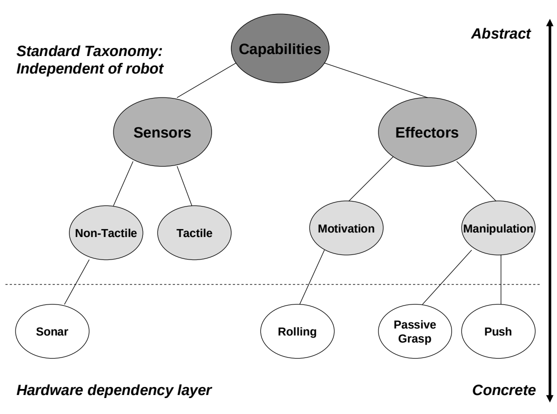

Figure 7: Amigobot Capability Taxonomy Model

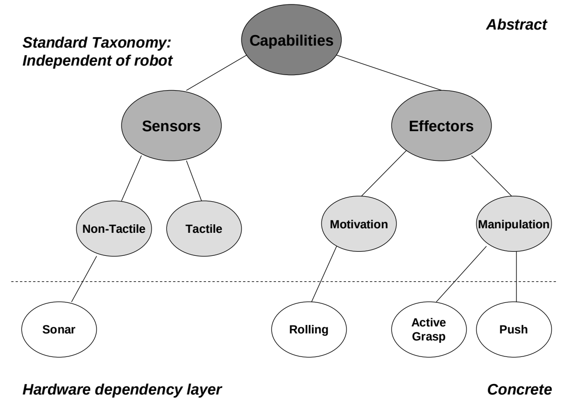

Figure 8: Pioneer 2 Capability Taxonomy Model

7. Results

To implement and test the viability of dynamic evaluation of robotic capabilities and its effects in relation to team organization, we first developed a Java simulation environment in which to test the organizational process algorithms. With the success of the simulation, we used the abstraction architecture to develop instances of robotic teams to further test the evaluation of capabilities and their effects on cooperative team self-organization.

7.1 Simulation Testing

In our evaluation, 100,000 dynamic capability evaluation tests were performed to determine the success ratio of the three organizational outcomes. Over this significant sample space, the simulation generated approximately 33% selection of each outcome. The simulations were successful, in the fact that in all cases the outcome agreed with the pre-determined capability taxonomy and the proposed outcome. This suggests the software implementation of the static organizational model was successful.

7.2 Robotic Team Instance Testing

There were fewer robotic instance tests, due to additional set up time and preparatory work. In each case, the predicted outcome occurred, but additional test runs will have to be executed before describing this as a complete success.

There are many environmental factors that can affect the sensor capabilities and therefore cause unforeseen problems with the evaluation of capabilities. In a complete field test, the effects of the environmental factors will potentially and probably change the success ratio.

With successful simulation testing and preliminary success in field testing, the results of this work are very promising. The work can be extended to larger teams with more complex taxonomy structures. This work is an advance in developing team implementations with the ability to dynamically evaluate their own capabilities and self-organize.

8 Future Work

In the future, we will extend the implementation to cover a full implementation of all classes in the organizational model. This will allow the development of a complete formal model for dynamically computing the global capability of any potential organization of cooperative robots or agents.

Another intention is to develop synthesis models for capabilities so that individual capabilities can be meshed together to create higher level capabilities. This will require a more complex, but more powerful, abstraction layer to materialize.

We also plan to develop Genetic Algorithm (GA) approaches to discover the capability taxonomy present in a specific robotic instance and current team of cooperative robots.

Acknowledgements

This research is supported by a grant from the Air Force Office of Scientific Research (AFOSR) under grant number F49620-02-1-0427.

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